12

THE ORBITAL STEAM LOCOMOTIVE

Put in your water and shovel in your coal.
Put your head out the window, watch them drivers roll!
I'll run her till she leaves the rail,
Cause we're eight hours late with the western mail!

From the US folksong *Casey Jones*,
attributed to Newton and Seibert (1909)

THE development of the American west, to a very large extent, depended upon the steam locomotive. Not only did the coal-driven trains of the transcontinental railroad transport the mail, but such items as tools, produce, and people were carried by this service.

Long before Casey Jones, and long before the taming of steam, people had investigated the physics of the steam engine. In fact, as briefly

discussed in Chapter 3, demonstrations of thrust produced by steam escaping from a vent may be the first historical application of the rocket principle.

In 50 BC, Hero of Alexandria constructed an "aeropile," which consisted of a boiler and two vertical pipes that were attached to a horizontal axle on which a hollow sphere was mounted. A vent was located within the sphere.

The boiler was filled with water. A fire was lit under the boiler; steam rose into the hollow sphere and was forced out of the vent. The reaction to this "thrust" caused the aeropile to spin, much to the delight of onlookers.

Perhaps, if this device had been productively employed in the Greco-Roman world, the Industrial Revolution would have dawned 1,500 years earlier! But alas, the application of the aeropile might have reduced the need for menial labor, and slavery was a sociologically important institution in the classical world.

Many centuries after Hero, engineers realized that the vented steam could be impacted against the blades of a turbine, and so the steamboat was born, in which the spinning turbine was itself attached to a paddlewheel. These water craft successfully competed with and ultimately replaced sailing ships. In the nineteenth century, the spinning turbine was attached to a wheel axle, miles of track were laid and the first coal-fueled locomotives began to chug across the landscape. Today, a new type of steamship is being considered. This one uses a very different type of steam and will travel between planets, not just across a continent. It is called a solar-thermal rocket.

SOLAR-THERMAL ROCKET FUNDAMENTALS

The operation of a solar-thermal rocket is presented in Figure 12.1. Unlike a chemical rocket, the Sun powers solar-thermal rockets. Using either a Fresnel lens or a parabolic mirror, sunlight is concentrated to superheat propellant, which is then vented to produce thrust. The concentrator is the key feature that distinguishes this technology from other propulsion technologies, heating the propellant with the equivalent of up to 1,000 Suns (at 1 AU). Recall that exhaust velocity and thrust are closely related to the propellant's temperature—and a solar-thermal system can make the propellant very, very hot.

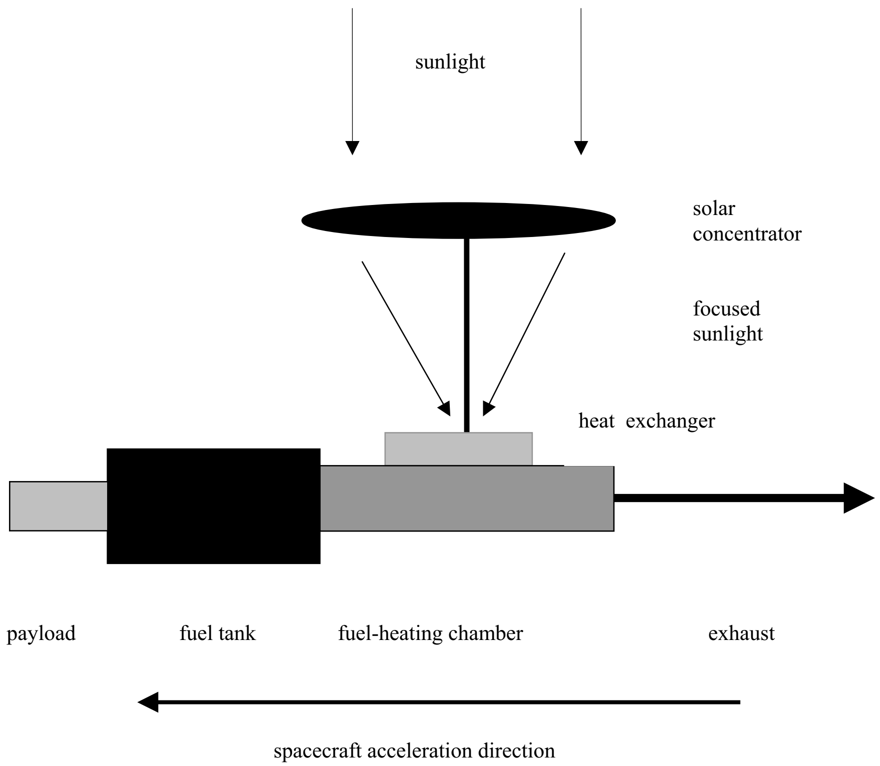


FIGURE 12.1 The solar-thermal rocket

Although very simple in concept, implementation is not so straightforward. One technical challenge is the heat exchange with the propellant. As one cannot directly heat a moving fluid in a vacuum, it must be done indirectly. In indirect heat exchange, the sunlight warms a material, or "heat exchanger," that subsequently transfers the heat to the propellant.

The fuel-heating chamber must be constructed of high-temperature materials. For optimum performance, propellant temperatures are well in excess of 1,000 degrees Celsius.

Although the working fluid (propellant) in Hero's device, steamboats and coal-stoked locomotives was water, optimum performance for solar-thermal rockets is achieved if a lower molecular mass propellant is used. Current prototype solar-thermal rockets use hydrogen propellant. If we replace hydrogen with water propellant, the exhaust velocity would decrease from about 10 kilometers per second to about 3 kilometers per second.

Although the use of hydrogen as a propellant results in high exhaust velocities (typically about twice those of the best chemical rockets) there

are significant drawbacks to employing this fuel on long-duration space missions. Liquid hydrogen is difficult to store in the space environment and, due to its very low boiling point of –252 degrees Centigrade, it tends to evaporate or "boil off." Even the cold temperatures of space are too warm to prevent hydrogen from turning into a gas. Hydrogen gas is notoriously difficult to store. Its low molecular weight and atomic size allows it to slip through very small cracks, making it virtually impossible to completely contain. As an alternative, some solar-thermal rocket systems are being designed to operate using methane, paying the performance penalty associated with its higher molecular weight and subsequent lower exhaust velocities, in preference to the long-term storage problems posed by hydrogen fuel.

In terms of thrust, solar-thermal rockets are intermediate in performance between chemical rockets and ion rockets. In part, because of the requirement for massive solar concentrators, no solar-thermal rocket will ever lift off from a planetary surface. But accelerations of 0.01 Earth gravity are possible in the space environment.

Near-Term Application of Solar-Thermal Rockets

NASA, the US Department of Defense, and other agencies are considering near-future applications of this technology. Perhaps the earliest application will be orbit transfer.

Assume that you've paid the launch cost to put a satellite into low Earth orbit a few hundred kilometers above Earth's surface and you wish to raise its orbital height to a geosynchronous altitude, about 36,000 kilometers above Earth's surface.

You could of course do this with a conventional upper stage using chemical propulsion, but a hydrogen-expelling solar-thermal rocket has about twice the efficiency of the best chemical rocket. So there is a significant economy in developing a solar-thermal tug to loft payloads between low Earth and geosynchronous orbits. This economy will be of interest to developers of communication, navigation, and Earth-viewing satellites.

But, as generally happens in the space business, there are trade-offs. A chemical rocket is a high-thrust device and the orbit transfer can be accomplished within hours or, at most, a few days. Although a solar-thermal rocket has a higher thrust than a solar-electric rocket, the orbit-

transfer time between low Earth orbit and geosynchronous orbit is considerably longer than for a chemical rocket.

Orbital-transfer tugs based upon the solar-thermal rocket (or the solar-electric rocket) are certainly feasible. But payloads on board these tugs will require more shielding during their transfer through Earth's Van Allen radiation belts than payloads on board chemical rocket orbital-transfer tugs due to the fact that they will be spending more time in the radiation belts, increasing the total radiation exposure and potentially causing more radiation-induced damage.

At least two flight tests of the technology were proposed in the 1990s. The Shooting Star Experiment was to have launched from the space shuttle orbiter and demonstrate the fundamentals of the technology. An artist concept for the Shooting Star is shown in Figure 12.2. Boeing, working with the US Air Force, was tasked to develop a space tug using solar-thermal propulsion called the "Solar Orbital Transfer Vehicle (SOTV)." Neither the Shooting Star Experiment nor the SOTV flew.

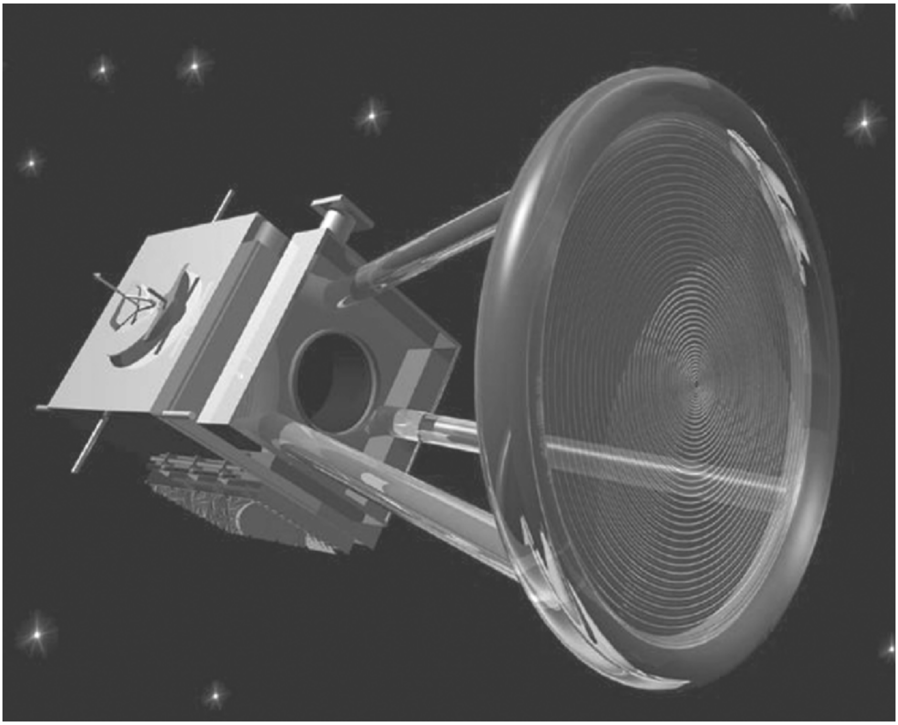


FIGURE 12.2 Artist's concept of NASA's shooting star experiment. (Courtesy NASA)

Possible Application of Solar-Thermal Technology to Solar-System Development

Solar-thermal rockets are ideally suited for "living off the land" in space. With sunlight as their source of energy and abundant hydrogen or methane as their fuel, they can operate anywhere within the orbit of Mars with relatively high thrust and high efficiency—a compromise between the best (and worst) of both chemical and electric propulsion systems. Departing the Earth with cargo, or returning to it with raw materials, solar-thermal-propelled spacecraft can carry large payloads fairly quickly and efficiently.

They can be refueled at comets, whose abundant water can be cracked into hydrogen and oxygen by passing through the water an electrical current and collecting the liberated gases in a process known as "hydrolysis." This might also be implemented at the Moon where water ice is thought to exist in forever-shadowed craters near the poles.

As well as its potential utilization as a space drive to shunt freight around the solar system, solar-thermal technology may be of use to future space-mining processes and industrialization enterprises.

The solar concentrators for a solar-thermal interorbit tug capable of ferrying large payloads will themselves be large. In one design described by Robert Salkeld and his collaborators, a 100-meter collector diameter is proposed. So a solar-thermal solar concentrator will have to be a low-mass item, with its thickness measured in microns. In order to heat the working fluid to the requisite high temperatures, the concentrator must also be precisely machined and capable of withstanding the space environment for long time periods. Near-term small satellite missions using solar-thermal propulsion would not have to be nearly as ambitious. Concentrators a few meters across are sufficient to produce thrust for missions in this class.

These large-scale concentrator requirements will be of great interest to those who would mine small solar-system bodies for water, other volatile substances, and higher melting point compounds or elements. A space miner might simply use the solar-thermal concentrator to focus sunlight on his or her asteroid and collect pure materials as they boil off.

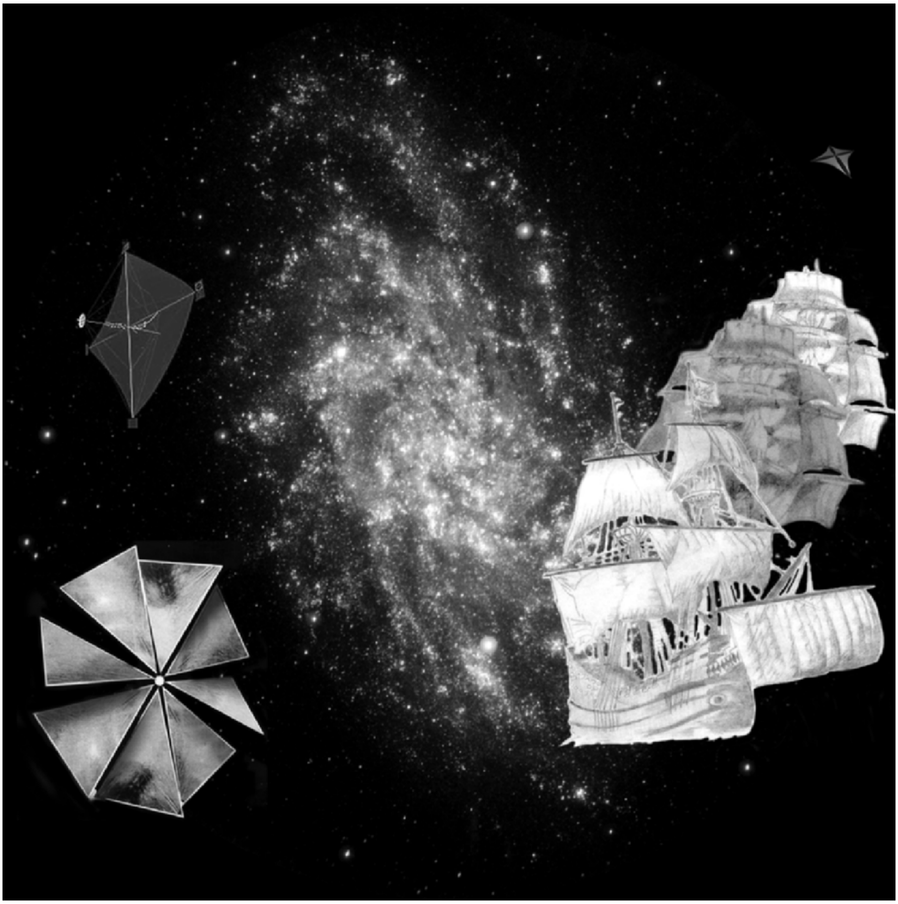
Further Reading

Hero's experimental aeropile is described by Carsbie C. Adams in his classic *Space Flight* (McGraw-Hill, New York, 1958). Some even earlier

experiments are mentioned by Eugen Sanger in *Space Flight* (McGraw-Hill, New York, 1965).

The relationship between solar-thermal (and nuclear-thermal) rocket exhaust velocity and propellant molecular mass is discussed by Martin J.L. Turner in *Rocket and Spacecraft Propulsion*, 2nd edn (Spinger–Praxis, Chichester, UK, 2005).

An early design for a large solar-thermal rocket is included in *Space Transportation Systems*, which was edited by R. Salkeld, D.W. Patterson and J. Grey and published by AIAA Press (Washington, DC, 1978). A much more recent consideration of the utility of solar-thermal solar concentrators in space mining is included in J.S. Lewis' *Mining the Sky* (Addison-Wesley, Reading, MA, 1996).



[See also Plate V in the color section]